

**A REPORT OF THE AAWG
RECOMMENDATIONS FOR REGULATORY ACTION TO PREVENT
WIDESPREAD FATIGUE DAMAGE IN THE COMMERCIAL AIRPLANE FLEET**

6.0 TECHNOLOGY READINESS

6.1 1998 ASSESSMENT OF TECHNOLOGY AVAILABLE

6.1.1 1993 Recommendations

The Industry Committee on Widespread Fatigue Damage (ICWFD) which worked under the umbrella of the AAWG defined research recommendations in their final report issued 1993. The research goals and subjects of interest for the industry for evaluation of Widespread Fatigue Damage were defined and are summarized in the table below.

Analysis goals	Research subjects
Initiation of MSD/MED	
Predict realistic cracking scenarios Define a lower limit for MSD/MED initiation	Cracking location Coupon testing for each susceptible area Statistical analysis Guidance material Scatter on material data Redistribution of loads
Propagation of MSD/MED	
Predict cracking development Step towards WFD occurrence limit Monitor MSD/MED	Short cracks: Influencing factors Short cracks: Parametric coupon tests Short cracks: Scatter in material data SIF: Non uniform cracks in complex geometry SIF: Crack interaction SIF: Crack deviation/ bulging/ cold working/ interference SIF: Redistribution of loads Scatter in material data
Residual strength	
Predict residual strength in presence of MSD/MED	RS of ductile materials in the presence of MSD/MED RS validation on large scale components RS: consideration of crack configuration/ curvature/ load transfer RS: consideration of in plane and pressure loadings
Risk analysis	
Predict WFD based on randomisation of WFD parameters	Common understanding of basic rules for risk analysis Develop guidance material Specific methods for WFD parameters
Discrete source	
Assess the real concerns with this issue Predict residual strength	Common industry data on discrete source Extend/ location/ type of damage determination Probability analysis (occurrence/ location/ extent)

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6.1.2 1998 Status

As a result of worldwide aging airplane activities, research programs were initiated in the United States and in Europe. Programs such as the FAA's National Aging Aircraft Research Program (NAARP), the European Group for Aeronautical Research and Technology in Europe (GARTEUR) Action Group and the European Brite EuRam Structural Maintenance of Aging Aircraft (SMAAC) Project were established.

The NAARP consists of seven major subjects, one of which deals with Structural Response Modeling and Simulation. Within this project the WFD research activities cover deterministic methodologies as well as probabilistic methodologies. Historically, the FAA research activities in the WFD area have been focussed on residual strength analysis and prediction. Additionally methodologies for crack growth analysis were developed. Furthermore, in 1996 the FAA and NASA jointly funded a contract with an American manufacturer to develop and validate a procedure for the prediction of the point of WFD. This activity included the evaluation and validation of several crack growth and residual strength analysis methods such as equivalent initial flaw size determination, FASTRAN, crack growth criteria T^* and Crack Tip Opening Angle (CTOA), Finite Element Alternating Method (FEAM), FRANC2D, FRANC3D/ STAGS. The research work included a large number of coupons, flat panels, stiffened panels, sub-scale cylinders, unstiffened curved panels, stiffened curved panels and aft pressure bulkhead panels sub-scale which were tested regarding fatigue, crack growth and residual strength to support and validate the analytical work. Additionally, probabilistic methodologies can predict the time-dependent probability of the point of WFD, the time dependent distribution of the airplane's residual strength, and the impact of inspections on the structural integrity of the airplane.

An initial collaborative program undertaken by the European aerospace community was started in 1994. This program was supported by the GARTEUR to increase the understanding of MSD in highly loaded joints, and to reduce some of the deficiencies in existing methodologies for predicting the development of MSD in such components. The activities of the project were completed in 1996.

Following the dissolution of the GARTEUR Action Group, financial support for continued collaboration in the field of WFD was secured from the European Commission under the Fourth Framework Program for Research and Technological Development (1994-1998). The GARTEUR activity, and the insights into the problem of MSD, which arose in consequence, were major contributing factors in the success of this proposal. The Brite/ EuRam project (SMAAC) which began in 1996 has the objective of develop engineering tools for the assessment of maintenance actions (inspection and repair) for aging airplanes, and to derive novel design methods to extend the design life of future airplanes with respect to WFD.

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The duration of the SMAAC project was originally planned to cover three years, and the project will therefore continue until the beginning of 1999. By the end of the SMAAC project, it is anticipated that a range of theoretical models will have been developed to assess fatigue crack initiation and propagation in aging airplane structures, in order to determine the maintenance actions required to preclude the point of WFD. These models cover the following areas: multiple fatigue crack initiation (probabilistic analysis), multiple fatigue crack growth (deterministic analysis), residual strength in the presence of MSD/MED (deterministic analysis) risk assessment and overall models.

The data base of experimental evidence of MSD/MED has also been increased through an extensive series of fatigue crack growth and residual strength tests, undertaken specifically for the SMAAC project. These test programs are principally intended to provide information to support the development of the analytical models. Therefore they consist of generic specimens, rather than specific airplane components, such as simple specimens (initiation and growth of MSD) and complex specimens (residual strength of representative stiffened panels, i.e. flat stiffened panels with lap or scarf joints, and curved panels with stiffeners, frames and longitudinal lap joints).

Linear elastic fracture mechanics methodologies have been generally adopted in the analytical approaches developed within both the GARTEUR and SMAAC projects, with stress intensity factor solutions obtained through a range of techniques of increasing complexity, such as compounding, stress functions, boundary element analysis and finite element analysis. By the end of the SMAAC project, the analytical models produced by the various partners will have been validated against these experimental results, which should also establish the level of sophistication required to address each of the given problems.

6.1.3 Future Research

With respect to the research programs described, the results of the round robin tests, see Section 8.6, and the overview of OEM methodologies, see Sections 8.1 through 8.5, the following research is recommended with the understanding that this research may not affect the first round of audits due in three years:

- Every effort should be made to make data from tests conducted in all research programs available at the earliest possible time before formal reports are issued.
- Extension of the analysis methods to thicker (wing) structure and verification by representative testing.
- Provision of equivalent initial flaw size (EIFS) data for all relevant alloys and fasteners. Fractography after fatigue testing to obtain cracks sizes versus time data, which each OEM could use to substantiate crack growth model and rate data.

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- Development of small crack da/dN data for some specific materials and configurations.
- Determination of the scatter in the initiation of MSD/MED for different structural configurations as developed in section 6.1.4.
- Tests currently funded, involving lead crack link-up, should be accomplished as soon as possible to support the first round of audits due in three years.

6.1.4 Research Proposal

Several manufacturers use a stochastic approach based on the Monte-Carlo simulation procedure to determine damage scenarios, which are the basis for the WFD evaluation. A series of initial damage scenarios are randomly defined taking material scatter into account.

Generally the material scatter of small coupon specimens is used, i.e. the scatter of cycles to failure of the specimens.

It is recommended the variability of MSD cracking for typical high loaded fuselage joints with high secondary bending be investigated. The investigation consists of constant amplitude tests with small and large coupons and of the comparison with tear down results from real airplane or large curved stiffened panel tests.

The following test program is proposed:

- Constant amplitude tests with small coupons (width one rivet pitch) up to crack initiation, microfractographic investigations to determine the life up to 0.005 and 0.05 crack length.
- Constant amplitude tests with large coupons (width six rivet pitches) up to crack initiation, microfractographic investigations to determine the life up to 0.005 and 0.05 crack length.
- Constant amplitude tests with small coupons (width one rivet pitch) up to failure.
- Constant amplitude tests with large coupons (width six rivet pitches) up to failure.
- Tear down and microfractographic investigation of realistic airplane structure to determine the life up to 0.005 and 0.05 crack length.

The goals of these investigations are to determine the scatter of the fatigue lives up to first 0.005 flaw, first 0.05 flaw and up to failure of the specimens and to compare the results with either data from in-service airplane or representative large panel tests. The joint configuration and the production standard has to be identical for coupons and airplane structural. However, the effect of production changes on the scatter should be investigated additionally.

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6.1.5 Residual Strength

The presence of MSD adjacent to a lead crack has a significant influence on the residual strength capability of the structure. Former concepts for residual strength evaluation used for type certification considered single damages. These concepts, e.g. Feddersen concept or R-curve approach, are not adequate for the residual strength evaluation in the presence of MSD.

More sophisticated approaches have been developed, e.g. J integral, T* integral, CTOA, elastic-plastic FE analysis, plastic zone link-up. To support these new approaches significant testing with flat and curved panels has been conducted in frame of the US National Aging Aircraft Research Program and the European Brite-EuRam SMAAC (Structural Maintenance of Aging Aircraft) Program. One of the purposes of the test programs is to demonstrate the residual strength capability of airplane structure potentially susceptible to WFD and to verify the concepts, methods and analysis tools for residual strength evaluation.

The U.S. National Aging Aircraft Research program includes testing of flat panels with lap joints, butt joints, and double shear joints to study residual strength affects of MSD. Additional residual strength tests of curved panels with spectrum loading that are representative of typical airplane structure will be conducted with MSD and MED present.

The European research program contains residual strength tests with flat specimens containing open holes, lap joints, double shear joints, butt joints and asymmetric joints for studying different aspects of the residual strength issue in the presence of MSD. Furthermore stiffened flat and curved panels with typical structure were tested under real loading. This structure represents the major fuselage and wing joints of existing small and large European airplanes.

Besides the tests included in the research programs, further residual strength tests are planned by the European and US manufacturers with specific structure of the airplane types to be evaluated regarding WFD. These tests will include major fuselage and wing joints and will validate the WFD analysis for these joints as well as allowing application of the experience to the remaining structure.

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6.2 1998 AND NEAR FUTURE INDUSTRY NDI CAPABILITIES

The AAWG reviewed current and future industry NDI capabilities in order to establish a baseline detectable flaw. The ability to detect small flaws in an inspection program is a key element in the decision an OEM must make in determining appropriate service actions. If flaws cannot reasonably be detected, then rework is the only recourse. If the flaws can be detected well before critical length, then a monitoring period approach could be employed to manage the service problem.

6.2.1 NDI Round-Robin

In order to determine the readiness of available NDI technology for use in the detection of MSD/MED, the AAWG devised a 'round-robin' survey, consisting of four sample problems on crack detectability in typical structural configurations. These problems were sent to each OEM (Airbus Industrie, Boeing Commercial Airplane Group and Lockheed Martin Aerospace Systems) and the FAA Technical Center for evaluation. In addition, the participants were invited to anticipate the minimum detectable crack size possible after 1 year and 5 years from the time of the survey, given the direction of current research and development in the NDI area. The basic problem statement and accompanying sketches are shown in Figures 6.2.1 and 6.2.2, respectively.

The results of this survey are presented on the following four pages, in which the estimates of crack detectability provided by each participant have been consolidated into a single minimum detectable crack size for each configuration. The detectable crack sizes specified by the OEMs in the survey were generally consistent; in most cases where differences existed, the consolidated results are the largest of the crack sizes provided, with 90/95 probability data used where possible. The information is believed to be conservative; it should be possible to stipulate smaller detectable crack sizes if the exact structural location is specified, rather than the typical scenarios suggested within this survey.

The NDI specialists participating in this survey repeatedly advised caution in the interpretation of the information supplied in response to the AAWG inquiries. The data sheets given on the following pages relate to crack detectability under controlled (laboratory) conditions, without consideration of other variables such as human factors, inspection surface conditions, and operator experience level. Furthermore, the data are based on the optimum NDI method, using 'state-of-the-art' equipment that may not be available to many operators. The simple numerical estimates of crack detectability presented in this section are therefore considered to be useful only as illustrations of typical NDI capability, and should not be used directly in engineering situations without an understanding of the many factors which influence non-destructive inspections.

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Nevertheless, the participants appreciated that the information on crack detectability was required by the AAWG in assessing the capability of the industry to ensure the elimination of the potential for WFD from the commercial airplane fleet. The survey provided the AAWG with a useful opportunity to discuss the problem directly with those NDI specialists in the best position to supply those data.

A complete compendium of data from each manufacturer is given in Appendix F.

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**NDI Round Robin
NDI Technology Issues For Discussion**

- In your perception what are the NDI Issues associated with the detection of WFD?
 - Multiple Site Damage (MSD)
 - Multiple Element Damage (MED)
- Summarize your major R&D thrusts in NDI that might aid in detection of precursory forms (e.g. MSD and MED) of WFD.
 - IRAD
 - CRAD
- What size of flaws can be reasonable detected in airplane structure (on airplane), with say 90 percent confidence, and 95 percent reliability for the cases illustrated by the figures on the next page?
- What would be the effect on the POD curve for a single detail verses multiple details (e.g. lap splices)?
- In your research initiatives how are the positive (both true and false) NDI findings enunciated and recorded?
- What are the estimated costs Vs detection capability on airplane structure for each of your research initiatives?
- What is the largest crack that can be missed in each of your methods?
- Have the methods you propose been validated on airplane type structure?
- With current research thrusts, what size flaws do you expect to be able to detect in:
 - 1 year?
 - 5 years?

Figure 6.2.1.1 NDI Technology Issues For Discussion

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**AAWG-TPG
ACTION ITEM 4-10
NDI FIGURES**

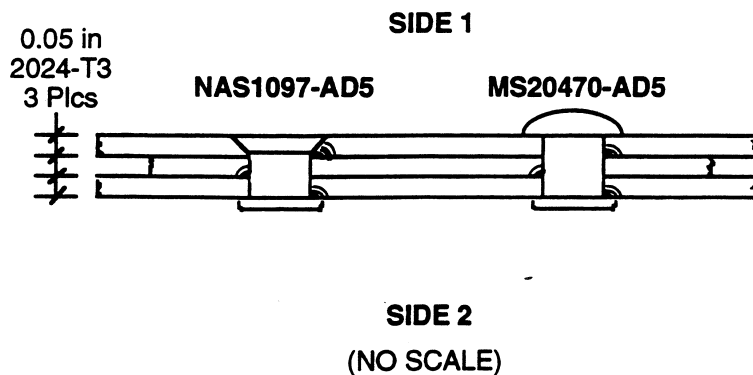


FIGURE 1. FUSELAGE TYPE STRUCTURE

Problem Statement:

- (1) For the six flaw locations shown in Figures 1 and 2, determine the 90,95 flaw size using your best candidate techniques from both SIDE 1 and SIDE 2?
- (2) What is the estimated false alarm rate?
- (3) What is the largest flaw that could be missed?

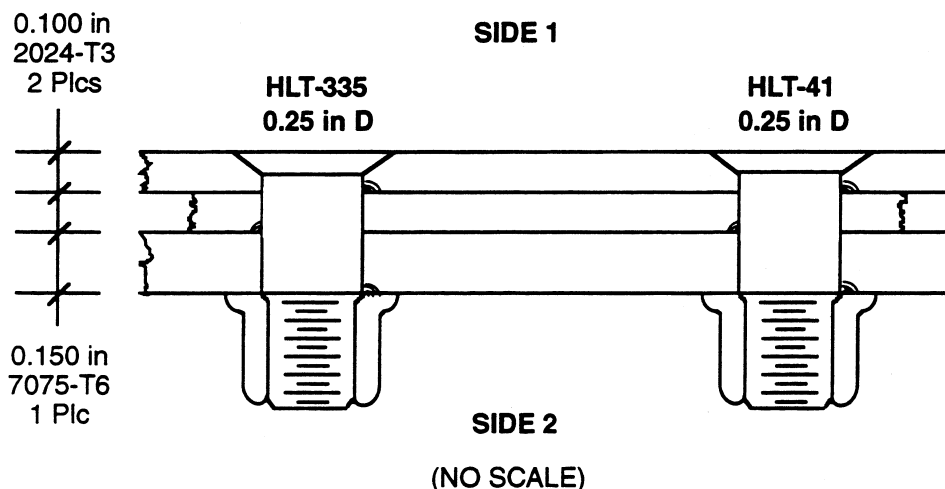


FIGURE 2. WING/EMPENNAGE TYPE STRUCTURE
Figure 6.2.1.2 NDI Example Problems

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6.2.2 NDI Round-Robin Results

6.2.2 Conclusions

The minimum detectable crack size was not found to have decreased significantly from the limits given at the time of the ICWFD report of 1993, despite the extensive research effort of the past five years. The current 'state-of-the-art' in NDI technology needs significant improvement in both detectability and reliability in the next three years to support audit alternatives for WFD.

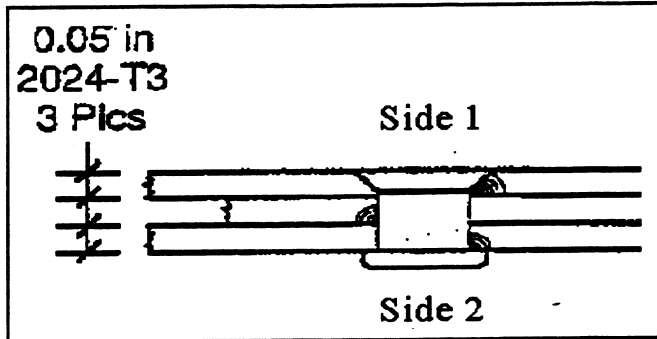
The highest potential to achieve the necessary improvements in crack detectability is in the field of semi-automated eddy current systems, incorporating new sensor technologies, multiple frequency application, automated signal pattern evaluation algorithms and documentation features. These advances are expected to result in a significant (20 to 40%) decrease in detectable crack size within the next five years with improved reliability.

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Widespread Fatigue Damage Detectability – Industry Estimate

(All cracks measured from shank of fastener, cracks numbered in ascending order from inspection side)

Case 1: Aluminum NAS1097-AD5 flush rivet



This data represents detectability under controlled (laboratory) conditions, using the optimum NDT method.

Human factors, inspection surface conditions, operator experience level, and other variables have not been considered.

Side 1:

	Industry Estimate	
	Inches	mm
CRACK 1:	0.05	1.3
	<i>0.04</i>	<i>1.0</i>
CRACK 2:	0.25	6.4
	<i>0.15</i>	<i>3.8</i>
CRACK 3:	0.31	7.9
	<i>0.2</i>	<i>5.1</i>

Side 2: Dimensions shadowed by upset rivet assumed to be 0.020 (0.5mm)
Rivet upset assumed to be irregular.

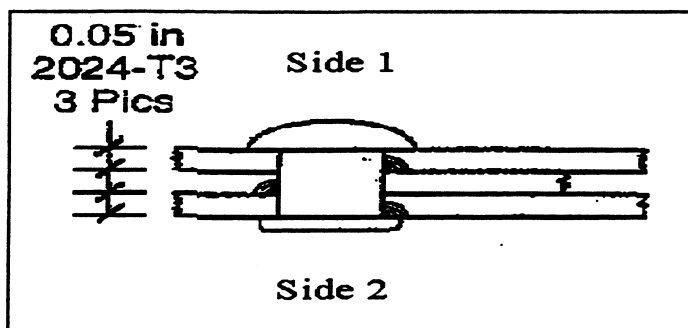
	Industry Estimate	
	Inches	mm
CRACK 1:	0.1	2.5
	<i>0.09</i>	<i>2.3</i>
CRACK 2:	0.25	6.4
	<i>0.15</i>	<i>3.8</i>
CRACK 3:	0.31	8.0
	<i>0.25</i>	<i>6.4</i>

Key: current capabilities in plain text, five year projections in *italics*, 90/95 crack lengths in **bold**

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Widespread Fatigue Damage Detectability – Industry Estimate

(All cracks measured from shank of fastener, cracks numbered in ascending order from inspection side)

Case 2: Aluminum MS20470 protruding head rivet



This data represents detectability under controlled (laboratory) conditions, using the optimum NDT method.

Human factors, inspection surface conditions, operator experience level, and other variables have not been considered.

Side 1: 0.078" (2.0 mm) = dimension shadowed by MS20470 protruding head

Industry Estimate		
	Inches	mm
CRACK 1:	0.12	3.0
	<i>0.09</i>	2.3
CRACK 2:	0.25	6.4
	<i>0.2</i>	5.1
CRACK 3:	0.35	8.9
	<i>0.25</i>	6.4

Side 2: Dimension shadowed by upset rivet assumed to be 0.078" (2.0 mm). Rivet upset assumed to be irregular.

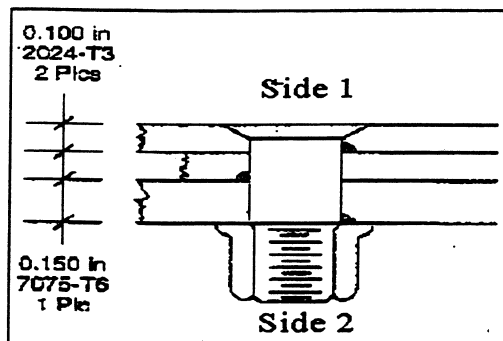
Industry Estimate		
	Inches	mm
CRACK 1:	0.141	3.6
	<i>0.098</i>	2.5
CRACK 2:	0.25	6.4
	<i>0.2</i>	5.1
CRACK 3:	0.31	8.0
	<i>0.25</i>	6.4

Key: current capabilities in plain text, *five year projections in italics*, **90/95 crack lengths in bold**

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Widespread Fatigue Damage Detectability – Industry Estimate

(All cracks measured from shank of fastener, cracks numbered in ascending order from inspection side)

Case 3: Titanium HLT-335 flush 0.250" (6.3 mm) diameter fastener



This data represents detectability under controlled (laboratory) conditions, using the optimum NDT method.

Human factors, inspection surface conditions, operator experience level, and other variables have not been considered.

Side 1:

	Industry Estimate		If fay sealed, with transducer access	
	Inches	mm	Inches	mm
CRACK 1:	0.2	5.1		
	<i>0.15</i>	3.8		
CRACK 2:	0.4	10.2	0.31	8.0
	<i>0.35</i>	8.9		
CRACK 3:	0.79	20.0		
	<i>0.5</i>	12.7	0.1	2.5

Side 2: Dimension shadowed by fastener collar assumed to be 0.125" (3.2 mm).
 No sealant cap present.

	Industry Estimate		If fay sealed, with transducer access	
	Inches	mm	Inches	mm
CRACK 1:	0.15	3.8		
	<i>0.13</i>	3.3		
CRACK 2:	0.425	10.8	0.39	10.0
	<i>0.375</i>	9.5		
CRACK 3:	0.675	17.1		
	<i>0.625</i>	15.9		

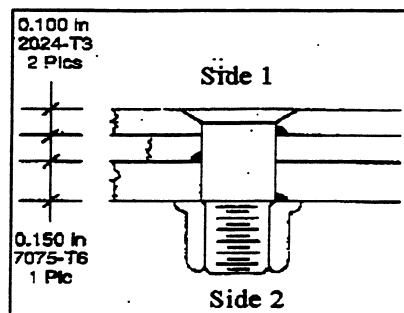
NOTE: Inspection for crack 3 from side 2 is a very unlikely inspection scenario.

Key: current capabilities in plain text, five year projections in italics, 90/95 crack lengths in bold

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Widespread Fatigue Damage Detectability – Industry Estimate

(All cracks measured from shank of fastener, cracks numbered in ascending order from inspection side)

Case 4: Steel HLT-41 flush 0.250" (6.3 mm) diameter fastener



This data represents detectability under controlled (laboratory) conditions, using the optimum NDT method.

Human factors, inspection surface conditions, operator experience level, and other variables have not been considered.

Side 1:

	Industry Estimate		If fastened, with transducer access	
	Inches	mm	Inches	mm
CRACK 1:	0.1	2.5		
	<i>0.1</i>	<i>2.5</i>		
CRACK 2:	0.3	7.6	0.31	8.0
	<i>0.2</i>	<i>5.1</i>		
CRACK 3:	0.55	14.0		
	<i>0.35</i>	<i>8.9</i>	<i>0.1</i>	<i>2.5</i>

Side 2: Dimension shadowed by fastener collar assumed to be 0.125" (3.2 mm). No sealant cap present.

	Industry Estimate		If fastened, with transducer access	
	Inches	mm	Inches	mm
CRACK 1:	0.125	3.2		
	<i>0.1</i>	<i>2.5</i>		
CRACK 2:	0.425	10.8	0.39	10.0
	<i>0.375</i>	<i>9.5</i>		
CRACK 3:	0.675	17.1		
	<i>0.625</i>	<i>15.9</i>		

NOTE: Inspection for crack 3 from side 2 is a very unlikely inspection scenario.

Key: current capabilities in plain text, five year projections in italics, 90/95 crack lengths in bold

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6.3 NDI Improvements with Regard to the Challenge of MSD

Residual strength reductions due to multiple site damage scenarios require appropriate measures in order to maintain the structural integrity over the period of planned flight cycles. Among other measures, improved and advanced NDI technologies is a candidate with a promising potential for the detection of MSD. Significant improvements in comparison with the currently available NDI technologies are expected from using the following technologies and computer software algorithms:

- Semi-automatic crack detection systems (manually operated probe systems with fully automated signal pattern evaluation)
- Improved multiple frequency eddy current systems
- SQUID sensor technology

All of the technologies mentioned above already exist today and have entered into advanced field trials. Further information on each of these technologies is given below. In order to fulfill the requirements for detection systems capable of reliably resolving the cracks associated with MSD, the improved NDI technologies must provide:

- A significant improvement in resolution capacity (20 to 40% over today's capability)
- Low false call rates (<1%)
- A reduction of the human factors element
- Semi-automatic signal pattern evaluation

Although new NDI technologies will certainly improve the detectability of fatigue cracks hidden in the second and third layer of structure, the highest potential for achieving the required improvements is seen in the field of semi-automated NDI systems incorporating new sensor technologies, multiple frequency eddy current applications, automated signal pattern evaluation algorithms and documentation features. Engineers involved in the NDI development process should interact with other disciplines that rely on their technology in order to establish requirements for detectability and reliability in the qualifications of new NDI technology. Such requirements, for future research, should be structured around the five most critical locations potentially susceptible to MSD for each OEM. The requirement should contain details about the manufacturing of the structure, expected flaw locations and direction of initiation and the expected crack shape over time.

The necessary improvements can be achieved within two to four years, provided that the activities of both American and European research institutes, academia, and OEMs are coordinated and financed by the organizations involved in aging airplane development activities.

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1. Semi Automated Crack Detection Systems

This system is based on eddy current and/or ultrasonic techniques. Semi automated systems are a combination of manually operated probes and fully automated measuring devices with software based on-line evaluation and classification of signal patterns. The fully automated measuring and evaluation algorithms of these crack detection systems eliminate the element of human factors to a high degree, thus making the inspection results much more reliable in comparison to current techniques. With the existing systems available in America and Europe combined with necessary improvements with regard to small crack detectability, semi automatic systems will become a major element in NDI applications for MSD detection purposes.

2. Improved Multiple Frequency Eddy Current Systems

Specialized vendors have offered various types of equipment for both rotating and sliding probe systems that make use of multiple frequency eddy current.

Use of these systems during teardown inspections and coupon tests have clearly demonstrated the advantages of multiple frequency systems with regards to:

- The identification of cracks
- The distinction between cracks, corrosion, permeability and geometry effects
- The determination of defect depth and size in hidden layers with an acceptable range of error.

As the existing systems have already demonstrated clear advantages in comparison with conventional ones, the development potential for multiple frequency eddy current applications should be thoroughly examined and exploited for MSD detection purposes.

3. SQUID Sensor Technology

SQUID technology (Super-conducting Quantum Interference Device) uses an extremely sensitive measuring element for the detection of magnetic field variations in combination with eddy current application.

This technology, driven by the academics, equipment manufacturers and OEMs in Europe, is offering a promising potential for improvements in fatigue crack detectability, particularly in hidden positions of lap splices and thicker multiple structural elements.

Due to the latest achievements in minimizing the dimensions of the cryostat device, the equipment has become portable so that it can be used under normal in-service maintenance conditions. Comparisons of PODs as achieved with the SQUID technique versus conventional equipment are showing equivalence on the tested structures but the SQUID technology is not yet considered to have reached the limits of its capabilities.